Mapping the Ice Zones of West Greenland Using Multi-Frequency Polarimetric SAR Data

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Abstract

Estimation of ice zones' extent and their temporal variations is fundamental for the retrieval of surface mass balance of glaciers and ice sheets. Several approaches have been proposed to map ice zones by means of Synthetic Aperture Radars (SARs), most of which are based on intensity measurements and their seasonal variations. Here, an alternative approach is investigated, which exploits co-polarimetric (co-pol) phase differences to detect the presence of firn. The approach is tested on a multi-frequency (X-, C- and L- band) dataset acquired by DLR's airborne F-SAR sensor over Greenland.

1 Introduction

The sensitivity of SAR sensors to discriminate between different ice zones was firstly reported in [1],[2] linking single-polarization backscattering coefficients to subsurface features. ERS-1 time series data were used in [3] to generate a mosaic of backscattering coefficients over whole Greenland to map the zones of the ice sheet. The first multi-polarization (and multi-frequency) study was presented in [4]. The relation between backscattering coefficients and the seasonal changes of some glaciers in Svalbard was investigated in [5]. Ice zones could be clearly distinguished in winter images and the firn line (FL) could also be detected. Multi-year data of the same glaciers revealed that the annual equilibrium line (EL) is rather difficult to detect and it might be possible only under certain conditions [6]. Based on a simple backscatter algorithm, firn masks were retrieved in [7] and [8] from C-band data to observe the FL retreat on two ice caps in Norway. A more advanced technique, based on statistical modeling of polarimetric covariance matrices, was developed in [9] to monitor the firn line position on a glacier in Svalbard. However, detecting thin and irregular firn layers characterizing, for instance, the transition between firn and ablation zones remain an open issue.

Recent studies have shown that information concerning firn and snow properties can also be extracted from phase differences of SAR backscattered signals [10],[11]. For instance, the physical model proposed in [10] established a link between HH-VV co-pol phase differences and the thickness and structural anisotropy of firn layers. The approach was employed to retrieve firn maps over two areas of a Svalbard ice cap [12]. The same approach is used in this study along a wide swath across Greenland, crossing different zones of the ice sheet. The objective is to assess the potential of such method to map the FL and to improve the mapping of irregularly distributed firn at the transition between the ablation and the firn zone.

2 Methodology

The approach proposed in [12] is based on HH-VV co-pol phase difference, defined as:

$$\phi_c = \phi_{HH} - \phi_{VV} \quad (1),$$

where ϕ_{HH} and ϕ_{VV} are the phase terms of the HH and VV channel, respectively. According to [12], non-zero ϕ_c values can be the result of propagation of the radar signal through firn layers, which are typically characterized by dielectric anisotropy [13]. The modelled polarimetric phase difference is expressed as a function of the firn thickness l, the permittivity components in the direction of the horizontal and vertical polarization, ε_h and ε_v respectively, the radar incidence angle ϑ and the wavelength λ_0 [12]:

$$\phi_c = \arg\left\{\int_0^l e^{-2j\frac{2\pi}{\lambda_0}\sqrt{\varepsilon_h}\frac{z}{\cos\vartheta}} \left(e^{-2j\frac{2\pi}{\lambda_0}\sqrt{\varepsilon_v}\frac{z}{\cos\vartheta}}\right)^* dz\right\}. \quad (2)$$

According to (2), the vertical anisotropy of firn explains only positive values of ϕ_c (unless phase wrapping occurs) and can be, therefore, used as an indicator for the presence of firn. The phase difference ϕ_c in (2) is also proportional to the firn thickness, so that larger phase differences can be associated to thicker layers and vice versa. Anyway, positive phase differences can also result from multiple reflections occurring within crevasses or from the propagation through a shallow layer of metamorphic snow. In the first case, ϕ_c is expected to show sharp variations at the location where the crevasse is, contrarily to the smooth pattern expected from a firn layer. Metamorphic snow is snow which accumulated in the current winter and has undergone temperature gradient metamorphism, similarly to firn. For this reason, it also possesses vertical anisotropy and can generate positive ϕ_c values as well. This can cause difficulties to distinguish a thin firn layer from metamorphic snow, especially at the transition between the firn and the bare ice zone. A further source of positive ϕ_c values can be ice surface corrugations in the ablation zone, which are expected to have a stronger impact with increasing frequency. In this case, multi-frequency data can help classifying correctly such features.

3 Polarimetric SAR Data

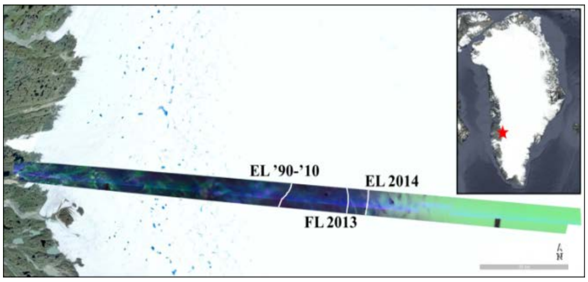

Figure 1: Pauli RGB representation of the two SAR scenes acquired over the K-transect. Red: HH-VV, Green: HV+VH, Blue: HH+VV. The white lines indicate the long term EL, the 2014 EL and the 2013 FL.

The dataset employed in this study was acquired by the DLR´s F-SAR airborne sensor in the frame of the ARCTIC15 campaign, on the 21st of May 2015. A 200 km long (and approx. 5 km wide) stripe was imaged at X-, C- and L-band in fully polarimetric mode, overflying the K-transect (67°04' N, 49°23' W), in West Greenland, along two opposite headings: from the ice margin up to the firn zone, crossing the ablation zone, and vice versa (see Figure 1). The data have a spatial resolution of 2.0 m x 0.5 m in range-azimuth at all frequencies. The incidence angle ranges from 25° in near range to 60° in far range.

The EL was located at approx. 1730 m a.s.l. in 2014 [14], while the long term EL, averaged over the period 1990-2010, is located at 1553 m a.s.l. [15] (see Fig. 1). Shallow ice cores from [15] found the presence of firn down to 1680 m elevation in spring 2013. Finally, snow accumulation reaches about 1 m at 1840 m elevation [16].

4 Experimental Results

4.1 Analysis of Polarimetric Phase Differences

Co-pol phase difference maps have been estimated at the three available frequencies for both headings with a final spatial resolution of approximately 20 m x 20 m. The maps are shown in Fig. 2(a) and (b) together with the elevation profile of the study area (Fig. 2(c)). The phase increase observed along the range direction of each heading is due to the increase of incidence angle, as explained in [12]. Phase values are generally positive, except for a few confined areas in the ablation zone at L-band and in the uppermost area at C- and X-band.

The phase difference pattern over the firn zone is very homogenous at L-band (top panel in Fig. 2(a) and (b)), with values increasing smoothly from 20° to 90° in range. A general decrease is observed between 1850 m and 1700 m elevation suggesting a decrease of firn in the area where the 2014 EL is located. This is in agreement with ground penetrating radar (GPR) measurements which reveal the presence of ice layers within the firn up to 1870 m a.s.l. [16]. Below 1700 m elevation, phase differences approach constantly 0°, indicating a substantial absence of firn, as confirmed by the estimated location of the firn edge at 1680 m a.s.l. [16]. C- and X-band show a behavior consistent to L-band in the lower part of the firn zone (1680-1900 m a.s.l.) where phase differences reach high values (up to 150°) already at middle range due to the shorter wavelengths. Interestingly, a different behavior is observed over the upper part of the transect. Here, C- and X-band phase differences are significantly lower than L-band values (Fig. 2b and 2c). A possible interpretation for this could be a joint effect of reduced penetration depth of the higher frequencies and the increase of fresh fallen snow at higher altitudes, which can cause negative HH-VV phase difference contributions [11].

In the ablation zone, below the firn edge, a dry snow layer covers the solid glacier ice. At L-band, this area exhibits small phase differences (either positive or negative), which can be explained with the presence of a thin layer of metamorphic (in the case of positive phase) or fresh snow (negative phase values). Nevertheless, some spots show larger values. A first look on the C- and X-band images suggests that such phase differences may be related to localized surface features. Optical images of the area support this as they show the presence of crevasse fields and rough surfaces in the lower part of the transect. Multiple reflections within crevasses can cause phase differences also at L-band, due to the large size (several meters) of such structures. Contrarily, surface corrugation is a smaller scale feature

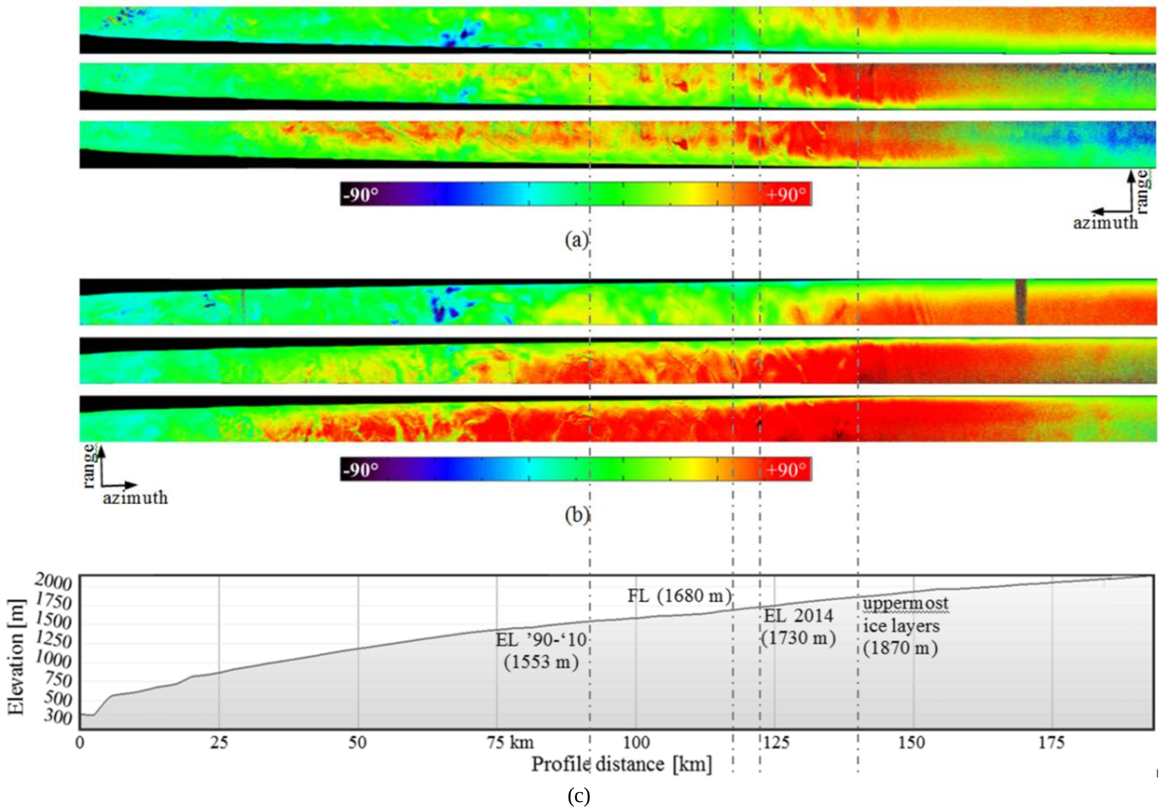

Figure 2: (a) L- (top), C- (mid) and X-band (bottom) polarimetric phase difference maps of the first and (b) second heading; (c) elevation profile of the study area.

and has, therefore, stronger impact at shorter wavelengths. This explains why larger phase differences are observed at C- and X- band in the ablation zone, where firn is absent.

5 Outlook and Conclusions

In this study, co-pol phase difference of L-, C- and X-band SAR measurements of the K-transect in Greenland are exploited towards a novel approach for firn mapping. First results suggest that L-band is better suited for this task. The higher penetration capability seems to provide a better sensitivity to firn and should allow to detect also firn layers buried below thicker ice layers. This allows a better characterization of firn distribution at the transition with the ablation zone and, consequently, an improved firn line detection with respect to methods based on backscattering intensity. In addition, L-band is less sensitive to surface roughness which has, instead, a strong impact on the C- and X-band polarimetric phase differences and limits their performance for firn detection. As a next step, the model in (2) will be employed to derive firn distribution maps from L-band phase differences. The potential to retrieve quantitative information about firn thickness will also be assessed, with the support of available in-situ measurements and results from other studies. The results of such investigation will be presented in the final paper.

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